Variability in physical contamination assessment of source segregated biodegradable municipal waste derived composts

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ABSTRACT

Physical contaminants (glass, metal, plastic and ‘other’) and stones were isolated and categorised from three finished commercial composts derived from source segregated biodegradable municipal waste (BMW). A subset of the identified physical contaminant fragments were subsequently reintroduced into the cleaned compost samples and sent to three commercial laboratories for testing in an inter-laboratory trial using the current PAS100:2011 method (AfOR MT PC&S). The trial showed that the ‘other’ category caused difficulty for all three laboratories with under reporting, particularly of the most common ‘other’ contaminants (paper and cardboard) and, over-reporting of non-man-made fragments. One laboratory underreported metal contaminant fragments (spiked as silver foil) in three samples. Glass, plastic and stones were variably underreported due to miss-classification or over reported due to contamination with compost (organic) fragments. The results are discussed in the context of global physical contaminant test methods and compost quality assurance schemes.

KEYWORDS: Compost quality; physical contaminants; impurities; in-vessel composting; ex situ; inter-laboratory trial

1. INTRODUCTION

Maintaining and improving compost product quality is vitally important for ensuring continued confidence in organic waste recycling industries. From the perspective of the general public and consumers, physical contamination is arguably the single most important quality criterion for organic waste derived products. Only last year for instance, physical contaminants (elsewhere known as foreign matter, impurities or inerts) in compost products going to land were highlighted in a UK prime time television programme, followed up by wider media attention. Despite its obvious importance, reported data on physical contaminants such as glass, metal and plastic in source segregated biodegradable municipal waste (BMW) derived compost is limited. Most studies instead focus on stability and maturity quality indicators (Aspray et al., 2015; Cesaro et al., 2015; Oviedo-Ocaña et al., 2015). In fact, only one article in the literature reports physical contamination in source segregated BMW derived composts (Dimambro et al., (2007). These authors comparing ten source segregated BMW derived composts alongside two mixed municipal solid waste (MSW) derived composts. The authors found that source segregated BMW composts had lower amounts of physical contaminants than MSW derived composts. Elsewhere further data on physical contamination in MSW derived composts can be found (Brinton, 2005; Montego et al., 2015; Sharifi & Renella, 2015). Therefore, additional data needs to be gathered on source segregated BMW derived compost to address this shortfall.

Tests for determining the abundance of physical contaminants in source segregated BMW compost products tend to follow the same basic procedure. In short, dry or wet sieving, manual isolation of physical contaminant fragments and, quantification on a weight basis. However, industry tests for individual countries show a number of key

differences. In the USA, for example, man-made ‘inerts’ such as glass, metal, plastic and synthetic textiles >4 mm are assessed on a weight basis (TMECC, 2001). By comparison in Germany, ‘foreign matter’ (glass, metal, plastic, rubber and composite materials) >2 mm, and stones >5 mm are assessed (BGK, 2003). The translated version of the German Compost Quality Assurance Organisation (Bundesgütegemeinschaft Kompost (BGK)) weight based test also states that paper, stones, lava and clay granulate should not be considered foreign matter.

The focus of this study is the UK test AfOR MT PC&S which is used to assess physical contamination of composts certified under the UK voluntary PAS100 certification scheme (B.S.I. PAS100:2011). The AfOR MT PC&S test is more complicated by comparison with both the TMECC and BGK weight tests in combining directly compost particle size distribution (PSD) and physical contaminant analysis in one. In addition, physical contaminants (>2 mm) must be classified as either glass, metal, plastic or ‘other’ with % w/w limits applied to both individual ‘plastic’ and ‘total’ (the sum of glass, metal plastic and other) categories. Unlike the BGK test, paper and cardboard are specifically identified as physical contaminants falling in the ‘other’ category. Finally, stones (>4 mm) are reported alongside physical contaminants and may include; aggregate, concrete, pebbles, pottery, rubble, tile and ‘any other consolidated mineral particles’.

A recent, albeit unpublished, UK study has found data inconsistencies between commercial laboratories following AfOR MT PC&S prompting the need to re-assess the test protocol. In addition, a key UK agriculture quality assurance scheme has recently successfully driven for lower physical contaminant limits (QMS, 2016) giving rise to further need to re-evaluate the robustness of the method. Specifically, compost going to Quality Meats Scotland (QMS) agricultural assurance scheme land

producing Scotch beef and lamb must not exceed half the PAS100:2011 permitted level of physical contamination (i.e. a reduction of the limits by 50 %). As QMS represents 90 and 80 % of Scotland's breeding cattle population and breed sheep stock respectively, the significance for compost going to the Scottish agricultural land banks is clear. Therefore, the aims of this research were to 1) identify aspects of the test protocol leading to apparent variability between laboratories and, 2) evaluate the robustness of the test for lower market specific limits. An inter-laboratory trial was chosen to assess these aims with testing carried out by commercial laboratories and supported by in-house analysis. The outcomes of the work provide useful information for wider physical contamination tests and compost quality assurance schemes. The research also adds to the currently scarce literature in characterising physical contaminants in source segregated BMW derived composts.

2. MATERIALS AND METHODS

2.1. Composts

Composts were collected from UK commercial sites during Winter 2014/2015 representing the three key product grades, as well as, different processes and feedstocks (Table 1). Twenty spot, or incremental, samples (>1.2 kg) were taken of finished compost products from batch piles after scraping away at least 50 mm of surface material as per the Renewable Energy Assurance Ltd (REAL) compost certification scheme (CCS) sampling guidelines (which are based on BS EN 12579:2013). Physical contaminant fragments were removed from (1.2 kg fresh weight) compost samples by hand (without drying to help maintain sample integrity) and classified into glass (>2 mm), plastic (>2 mm), metal (>2 mm), 'other' (>2 mm) and stones (>4 mm). The fragments were weighed before and after drying, and after

removal of loosely bound organic material (by gentle shaking in closed Petri dishes). Moisture content of compost aliquots was determined gravimetrically by drying overnight at 105 °C. The clean compost samples were weighed to 1 kg fresh weight, bagged and stored at 4 °C until spiking (section 2.2).

2.2 Inter-laboratory trial

Cleaned compost samples were spiked at two loading rates of physical contaminants according to the type of contaminants present originally in specific compost grades (Table 2). The high loading rate was chosen as the current PAS100:2011 limits for total (sum of glass, metal, plastic and other) contaminants. The low loading rate was chosen as 50 % of the current PAS100:2011 limit for total contaminants; now a market specific limit for compost going to certain land for meat production as stated above (QMS, 2016). The contaminants introduced were real fragments (isolated from the same compost material), augmented by post-consumer materials from other sources (e.g. broken glass, plastic bags and bottles). Post-consumer materials were used specifically for high contaminant loadings where it was deemed an insufficient number of consistent (in terms of both weight and appearance) fragments recovered directly from the compost samples were available. The specific materials were; 1) a shattered (rather than splintered) clear glass panel, 2) a clear rigid LDPE drinks bottle and, 3) larger film plastic fragments from a compost recycling facility wind sifter. Pieces were either sieved or cut into different sizes for use in the three compost grades appropriately.

Three commercial laboratories appointed to the REAL CCS participated in the inter-laboratory trial and were expected to follow the AfOR MT PC&S method. Each laboratory tested three samples per loading rate for the three contrasting compost

products. Clear sealable bags were supplied to the commercial laboratories labelled with sample number and physical contaminant type e.g. ‘1.1 glass’. The laboratories were asked to place contaminant fragments found in these bags and return them by post. The purpose of this was to confirm whether introduced fragments had been placed in their correct categories and allow correction of data if composts had not been completely cleaned before spiking.

2.3 Statistical analysis

Physical contaminant and stone abundance was compared between sites 1-3 using one-way ANOVA and Tukey HSD post-hoc analysis For the inter-laboratory trial weight data, a linear regression model was constructed for each contaminant type, using ‘lab’ (categorical) and ‘spiked’ weight (continuous) as predictors. For the inter-laboratory count data, a quasi-binomial generalized linear regression model was constructed for each contaminant type, using the number of ‘spiked’ fragments as denominator and the ‘lab’ (categorical) as predictor. All calculations were carried out using R statistical software (Version 3.1.0).

3. RESULTS

3.1 Physical contaminant characterisation in original compost samples

The mean % w/w of physical contaminants and stones originally isolated from three finished composts is shown (Table 1). Taking into consideration feedstock, the in-vessel compost (site 1) had higher mean glass contamination than the two composts processing only green waste. However, no statistical significance could be attributed to this due to noisy data resulting from 7 (site 2) and 8 (site 3) samples not containing ‘glass’ compared to all samples (n=20) for site 1. By contrast one or both

green waste only composts (site 2 and 3) had significantly higher levels of rigid and/or film ‘plastic’ ($p<0.05$), ‘other’ ($p<0.05$) and ‘stones’ ($p<0.01$). All three composts had ‘metal’ (exclusively found as silver foil) in a number of samples, however, usually only one or two small fragments, the weight of which was below the reporting threshold for sites 1 and 2. Two samples from site 3 had ‘metal’ contamination above the reporting limit. ‘Other’ contamination was found in all except 1 sample (Table 3). In the in-vessel compost (site 1) samples this was typically paper and cardboard. One of the green waste composts (site 2) had a wider range of ‘other’ man-made physical contaminants as indicated (Table 3). This included different foam fragments types which, despite being polymer based, were placed in the ‘other’ category primarily based on physical feel which was drastically different from rigid and film polymers placed in the ‘plastic’ category. For example, sample 9 from site 2 contained green floral foam used for flower arrangements; a very friable material. Foam fragments in other site 2 samples were spongy and tended to be brown in colour, stained during composting and only showing their original colour when broken into pieces exposing clean surfaces.

3.2 Inter-laboratory trial and commercial laboratory testing variability

Results of the inter-laboratory trial are presented in terms of spiked vs. lab ‘recovered’ weights (Figure 1). In addition, spiked vs. lab ‘recovered’ fragment numbers were also analysed (Figure 2).

Based on the weight data (Figure 1), the results suggest that the laboratories were fairly consistent in performance for glass, stone and (rigid and film) plastic fragment recovery. Maximum spike recoveries clearly support this for stones with maximum recovery rates between 104-108 % for all three laboratories. However, glass

minimum recovery rates for laboratory A was significantly below those of laboratories B and C. All three laboratories clearly struggled to find ‘other’ fragments (largely introduced into the three compost products as paper and cardboard due to the dominance in original samples) illustrated by the negative correlation coefficients. Metals were only spiked in three samples (due to a lack of suitable material arising from cleaning composts from sites 1 and 2); laboratory A failed to report all introduced silver foil fragments whereas laboratories B and C had minimum recovery rates of 80 and 100 % respectively. On a weight only basis, laboratory A had the worst performance for glass, plastic, metal and stones.

The spiked vs. ‘recovered’ fragment number data (Figure 2) showed a similar trend for glass as for the weight data with greater under-reporting by laboratory A at higher loadings. Based on the inspection of returned contaminant fragments, we found there was discrepancy in the classification in low loaded samples for site 1 (the 0-10 mm product). At least one laboratory classified fragments of introduced glass (between 2-8 mm) as quartz and reported these under ‘other’ contamination (leading in part to the observed weight over-reporting).

Plastics (rigid and film) were applied at a consistent fragment number (six) in all compost samples hence why data points are aligned as a single column in the relevant plot (Figure 2). Plastics were consistently and accurately reported by laboratory C; with weakest performance again by laboratory A.

For stones, higher loaded samples (sites 2 and 3) were underreported by all three laboratories resulting from missed fragments (particularly at the size range 4-8 mm); overall minimum recovery rates were between 39 and 54 %.

Finally, the fragment number data confirms the weight underreporting of ‘other’ contaminants (largely introduced as paper and cardboard) and compounded with

only one laboratory reporting ‘cardboard’ in the appropriate description box of the customer results certificate. Fragments of compost recovered foam (polystyrene-like material) were introduced in compost samples from site 2 only. Two of the three laboratories returned some (not all) foam fragments. Fragments returned after the trial showed that foam material was reported in the ‘other’ category by laboratory C and both ‘other’ and ‘plastic’ by laboratory B for different samples.

4. DISCUSSION

4.1 Physical contaminant characterisation in original compost samples

As might be anticipated, the nature of the feedstock(s) appeared to have some influence on the physical contaminants present in finished composts, with green and food waste derived compost (site 1) containing a higher level of glass than green wastes only derived compost (sites 2 and 3). Our results therefore support previous findings by Dimambro et al., (2007), who found a similar level of glass contamination (0.1 % w/w) in green and food waste derived composts compared to composts derived from green waste (in combination with milk, cardboard or fruit/vegetable feedstocks) where glass was below the report limit (<0.1 % w/w). However, it is difficult to draw a similar comparison for ‘plastic’, perhaps suggesting a greater influence of onsite management practices on the abundance of this contaminant type (e.g. material reception and picking line screening and/or, product clean-up technologies (e.g. wind sifting)). In composts from all three sites looked at, plastic contamination levels were towards the lower end of those previously studied (Dimambro et al., 2007). Given the uniqueness of the AfOR MT PC&S test, and the aforementioned lack of data on source segregated BMW derived composts, there is no directly comparable data on ‘other’ contaminants in the literature.

4.2 Paper/cardboard as physical contaminants

All except one original sample contained ‘visible’ fragments of paper and/or cardboard - two fragment types identified in the AfOR MT PC&S test as potential physical contaminants falling into the other category. The specific inclusion of wording relating to paper and cardboard as potential contaminants in the AfOR MT PC&S test protocol is not replicated in US (TMECC) or Germany (BGK) test protocols. The inclusion is particularly interesting given paper and cardboard may be used as carbon rich compost feedstocks in their own right (Venelampi et al., 2003). In fact, in the work by Dimambro et al., (2007) paper and cardboard were used as significant feedstocks for 5 out of 12 UK composts studied. However, the concern around paper and cardboard as potential physical contaminants in compost products is supported elsewhere. Specifically, WRAP (2007) trial work on composting cardboard waste acknowledges that care should be taken when using such material as a feedstock that this does not impact on resulting compost product quality. Associated with this work, Association for Organics Recycling (AfOR), now the Organics Recycling Group of the Renewable Energy Association, previously issued a guidance document which stated that ‘physical contaminants include visible fragments and clumps of paper and cardboard’ (AfOR, 2009). As biodegradable paper and cardboard are suitable feedstocks for composting, the AfOR MT PC&S test could be altered to report these potential physical contaminants separately to allow compost producers to better monitor their breakdown in processing and/or batch/seasonal variability. On this latter point, WRAP (2007) found from stakeholder engagement that cardboard represented a higher proportion of feedstock (~ 75 %) in winter (the period when our samples were collected) compared to summer (~ 10 %)

periods. In fact, when cardboard represented 20 % (wet weight) of feedstock it was found in trial work not to degrade well compared to lower % loadings (WRAP, 2007). AfOR (2012) have since provided guidance on the assessment of suitable paper and cardboard input materials, however, guidance on the assessment of 'visible' fragments in finished composts is lacking – the results of the inter-laboratory trial would suggest that this needs further consideration to improve consistency.

4.3. Physical contamination heterogeneity

Physical contaminant analysis of compost batches is known to be variable and our analysis of individual samples from finished composts piles are no exception with wide variability, particularly in site 2 and 3 products. One potential solution to this might be to take and analyse multiple samples to derive a value more representative of a whole compost batch. The downside to this would be increased analysis costs for compost producers, which in the UK is a complex test method incorporating PSD, as well as, the classification of physical contaminant fragments by size fraction.

4.4. Physical contamination threshold limit reduction

Based on an initial assessment of the protocol, and supported by the inter-laboratory trial, there was no apparent issue with the weight based method for physical contaminants even with the 50 % reduction in threshold limits. The test protocol specifies a balance weighing to two decimal places and a similar reporting threshold which should remain robust. In practice the new lower limits were found to require multiple fragments to trigger sample failures regardless of the physical contaminant category or compost grade being considered.

4.5 Isolation and classification of physical contaminants from compost by commercial laboratories (inter-laboratory trial)

Designed primarily to assess variability in analysis between different commercial laboratories, the trial identified several issues with the current test protocol. The first of these was the miss-classification of isolated fragments of glass and quartz prompting consideration of potential solutions to this problem. Although borosilicate glass is naturally fluorescent, many glass fragments found in compost are not, suggesting little/no benefit as a rapid screening technology using UV light. Initial assessment, supported by the inter-laboratory trial results found that coloured (green, brown and blue) glass is fairly easy to differentiate from natural quartz even as fragments (2-4 mm). However, 2-4 mm fragments of white quartz can be misclassified as glass (and vice versa) by naked eye alone. Although not readily apparent by naked eye, quartz fragments will exhibit a crystalline pattern whereas glass is an amorphous (non-crystalline) solid. Interestingly, the TMECC (2001) test actually qualifies that quartz unlike glass has a crystalline structure, suggesting a similar statement should be incorporated into other compost assurance scheme test method documentation. However, this may not be enough help for <4 mm fragments. Brinton (2005) sets 4 mm as a practical limit for separation of physical contaminants by naked eye in work on mixed MSW derived compost. In fact, the TMECC test adopts a threshold of 4 mm for physical contaminants presumably for this very reason. Therefore, other schemes (such as UK and German test protocols) should consider this further or at the very least emphasise the use of a magnifying glass to support classification of the smallest size (2-4 mm) fragments. The inter-laboratory trial highlighted that these fragments are difficult to classify by naked eye in the

laboratory which supports the exclusion of such fragments as found in the US test. However, before this can be considered, further information is needed to determine the abundance <4 mm physical contaminant fragments in composts and the impact of these specific fragments (especially glass) following compost application/use.

In the inter-laboratory trial one commercial laboratory did not report metal fragments from compost samples spiked with aluminium silver foil. Two possible reasons for this are that the specific analyst did not find these fragments or that the fragments were found but were under the weight threshold limit and so not reported. As no metal fragments were returned by the commercial laboratory following the trial the former is assumed the case. Therefore, consideration was also given to what low cost laboratory scale methods could aid identification of metal fragments. A handheld metal detector (Garrett Ace 150) was tested for screening silver foil (data not shown), however, fragments which were not clearly recognisable by naked eye were undetectable by the metal detector at close range even in the absence of compost and so not pursued further. In addition, as the other two laboratories did not have a problem with finding the metal fragments in the inter-laboratory trial, it may suggest that the fragment type isn't inherently difficult to find or identify and could be addressed with the introduction of a proficiency certificate scheme for analysts. Such a scheme exists for the asbestos in soil analysis which like physical contamination analysis in compost has a very high level of human decision making.

The trial also clearly showed variability (and under-reporting) of paper and cardboard contamination. However, as already discussed, uncertainty over what is 'visible' paper and cardboard contamination needs further consideration before concluding whether the isolation of these specific fragments is in fact difficult. That said the commercial laboratories clearly had difficulty with the other category beyond paper

and cardboard. For example, isolated quartz and graphite fragments (>4 mm) being included in the ‘other’ rather than stones category. One laboratory also reported on the customer test certificate ‘unknown’ physical contaminants isolated from the cleaned compost samples. As these fragments could not be identified it questions whether they should be identified as such. Based on the problems with the other category in the trial, it would seem appropriate to generate an exhaustive list of acceptable physical contaminants with codes similar to that shown here (Table 3). It might also be reasonable to argue that fragments which cannot be clearly identified as physical contaminants by eye should be excluded, especially given the primary reason for analysing physical contamination in the first place is because of visual appearance rather than a specific risk to humans or the environment.

Going forward it maybe more logical to categorise solid foam fragments in ‘plastics’ alongside rigid and film polymers despite the laboratories here tending to categorize these fragments in ‘other’ because of their different feel. However, this assumes that the introduced foam fragment was solely polymer based (currently untested). In this respect it should be noted that there is an increasing diversity of polymer composites including those composed of foam and plant fibres now being produced (Moscoso et al., 2013). Therefore, classification of composite fragments based on visual assessment alone also needs consideration, especially for the UK test where there are both ‘plastic only’ and ‘total’ weight limits.

CONCLUSIONS

Our conclusions from this work are:

- Physical contamination is heterogeneous in source segregated biodegradable municipal waste derived composts and may require replicate analysis to provide a fair assessment of product quality
- Weight based determination of physical contamination in BMW derived compost products appears robust even with imposed lower limits.
- ‘Other’ contaminants, especially paper and cardboard, are variability reported by laboratories. Guidance on when paper and cardboard are degraded sufficiently to no longer be considered ‘visible’ physical contaminants needs developing.
- Small (<4 mm) contaminant fragments of clear glass and quartz can be interchangeably misclassified supporting the use of higher size cut-off as found elsewhere.
- The ‘other’ contaminant category caused problems beyond the variable reporting of paper and cardboard. Specifically, the current protocol could be improved to better support the correct and consistent classification of fragments. For example, introduced in a subset of samples, solid foams were variably classified in ‘other’ and ‘plastic’. Otherwise, in one example an ‘unknown’ contaminant fragment was added to the other descriptor column of a customer report from the inter-laboratory trial. Therefore, more detailed descriptors and/or an exhaustive list should be developed for ‘other’ contaminant category.

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Table 1. Original physical contaminants in 20 spot samples from finished compost piles with significant differences between sites indicated by superscript lettering

Site	Product Grade	Feedstock	Composting Process Type	Physical contaminants (% g/g DM)					
				Glass (>2 mm)	Metal (>2 mm)	Plastic (>2 mm)	Other (>2 mm)	Total (>2 mm)	Stone (>4 mm)
1	0-10 mm	GFW	In-vessel	0.14 (0.08)	<0.00	0.03 (0.02)[a]	0.04 (0.03)[a]	0.21 (0.09)	2.16 (0.99)[a]
2	0-25 mm	GW	Open windrow	0.03 (0.05)	<0.00	0.10 (0.09)[b]	0.23 (0.22)[b]	0.37 (0.26)	12.32 (4.10)[b]
3	0-40 mm	GW	Open windrow	0.08 (0.17)	0.06 (0.26)	0.06 (0.07)[ab]	0.22 (0.26)[b]	0.41 (0.45)	12.33 (6.56)[b]
PAS limits						**0.12**		**0.25**	**8 or 10***

*Limit for mulches.
GFW – green and food waste; GW – green waste; PAS – publicly available specification (for composted materials)
Standard error in parenthesis
[a,b] Columns with different letters are significantly different (one-way ANOVA, $p<0.05$)

Table 2. Spiking of physical contaminants both on a % weight (and fragment number in parenthesis) basis. The % weight shows the narrow range achieved for spiked compost samples provided to the commercial laboratories using real physical contaminant fragments

ID	Product Grade	Contaminant Loading	Physical contaminants % g/g DM and fragment number					
			Glass (>2 mm)	Metal (>2 mm)	Plastic (>2 mm)	Other (>2 mm)	Total (>2 mm)	Stone (>4 mm)
1	0-10 mm	Low	0.07-0.11 (6*)	n/a	0.01-0.03 (6)	0.00-0.03 (3)	0.11-0.14	0.86-1.89 (32)
		High	0.23-0.28 (14)	n/a	0.01-0.02 (6)	0.00-0.01 (3)	0.26-0.29	0.72-1.34 (32)
2	0-25 mm	Low	0.04-0.06 (2)	n/a	0.04-0.06 (6)	0.01-0.03 (2)	0.11-0.12	4.46-6.10 (27)
		High	0.30-0.32 (8)	n/a	0.01-0.06 (6)	0.01-0.03 (2)	0.34-0.40	4.52-6.59 (27)
3	0-40 mm	Low	n/a	0.00-0.02 (3)	0.08-0.10 (6)	n/a	0.08-0.12	5.01-9.41 (28)
		High	0.09-0.21 (2)	n/a	0.08-0.12 (6)	n/a	0.17-0.34	4.62-7.06 (28)

*with the exception of two samples which each had seven fragments

n/a – not applicable

Table 3. Identified 'other' contaminant fragment in original compost samples

Sample	Site 1	Site 2	Site 3
1	P,CB	P,CB,TX	P,CB
2	P,CB	P,CB	P,CB
3	P,CB	P,CB,TX,R	P,CB
4	P,CB	P,CB,TX,R	P,CB,TX,R
5	P,CB	P,CB,S,F	P,CB
6	P,CB	P,CB,TX	P
7	P,S,CO	P,CB,TX	P,CB
8	P,CB	P,CB,TX,R	CB
9	P,CB,CO	P,CB,S,F	CB
10	P,CB	P,CB	-
11	P,CB,R,CO	CB,TX	CB,CO
12	P,CB,S,R	CB,OF,R	CB
13	P,CB,TX	CB,S,OF,CO	CB
14	P,CB,D,CO	CB,S,F	P,R
15	P,CB,TX	CB,TX,F	P
16	P,CB,CO	CB,S,R	S,TX
17	P,CB,S,CO	P,CB,S,F	CB
18	P,CB,TX	CB,TX	CB,TX
19	P,CB	P,CB,S,F	P,CB,R
20	P,CB,CO	CB,CO	CB,TX

P – paper; CB – cardboard; S – string/rope; TX- textile; F – polymer foam; R – rubber/silicone/resin; CO – composite (i.e. paper/plastic/aluminium)

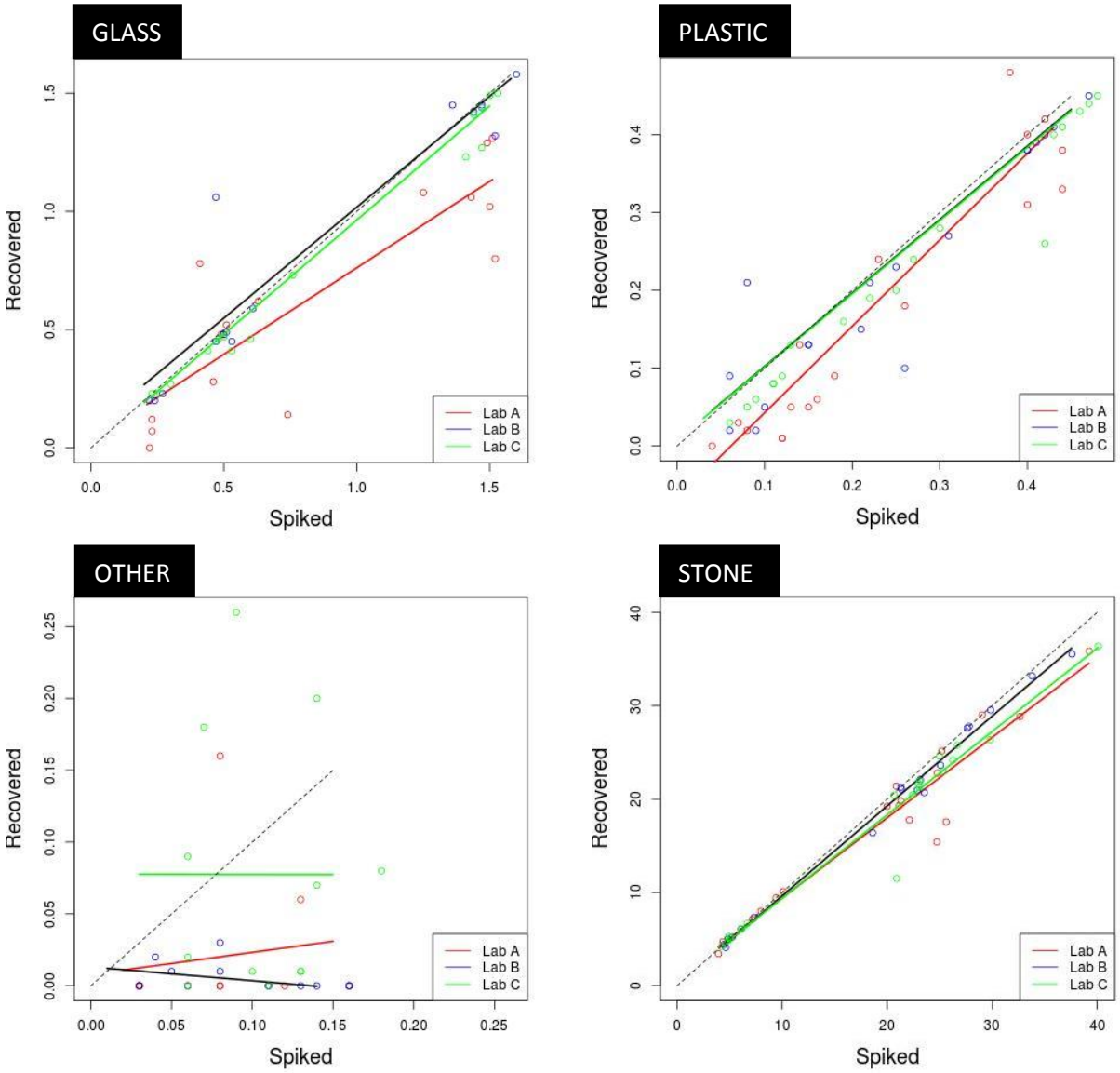

Figure 1. Spiked vs. lab reported physical contaminant fragment weight results for three commercial laboratories (A-C). The dashed line in each graph indicates the anticipated direct correlation between spiking and recovered results

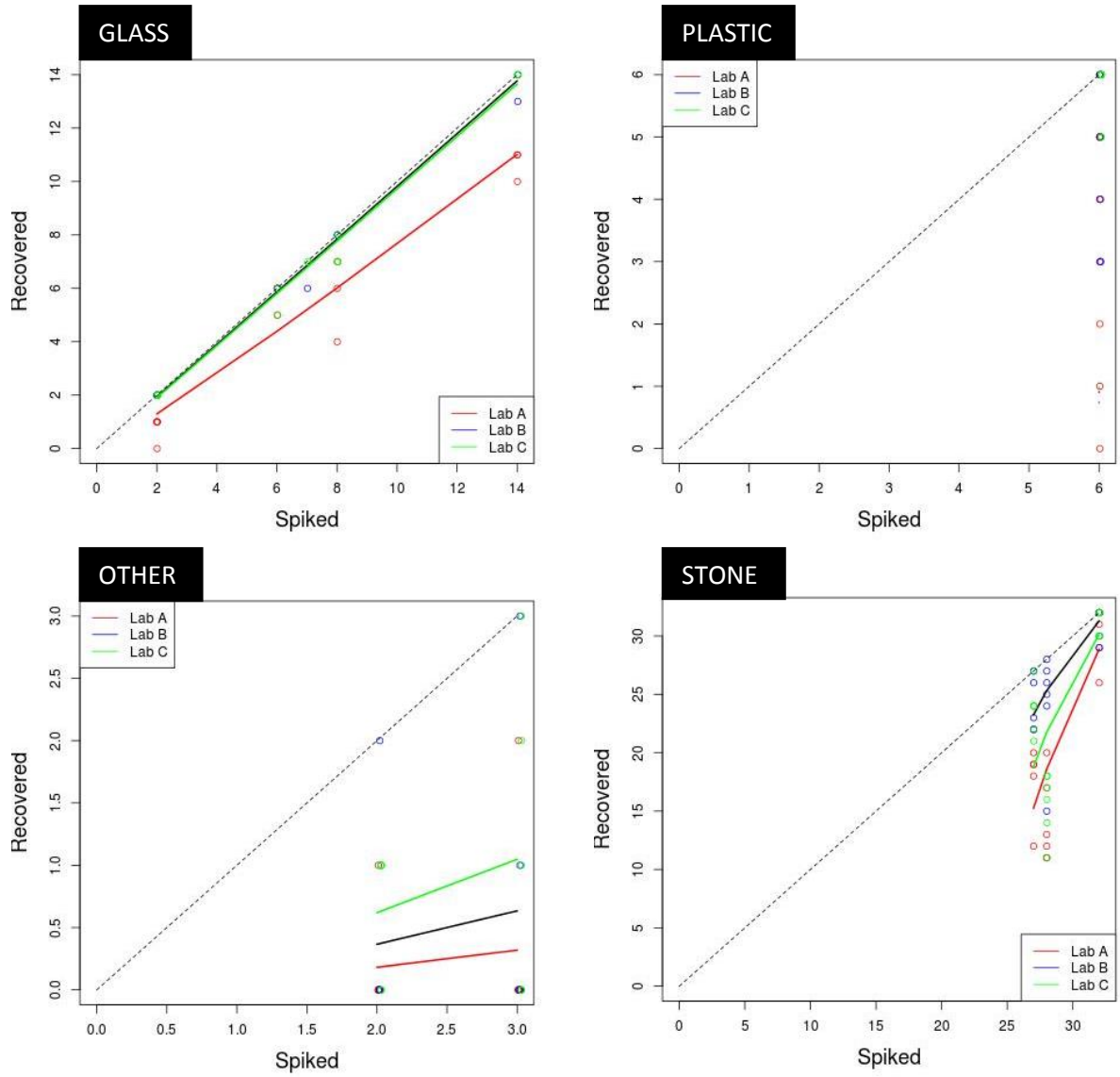

Figure 2. Spiked vs. lab recovered physical contaminant fragment number for three commercial laboratories (A-C). The dashed line in each graph indicates the anticipated direct correlation between spiking and recovered results